REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 20-06-02	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE **The USAF Electric Propulsion Research Program**		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Ronald A. Spores,[1] Mitat Birkan[2]		**5d. PROJECT NUMBER** 4847 **5e. TASK NUMBER** 0052 **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) [1]Air Force Research Laboratory (AFMC) AFRL/PRSS 1 Ara Drive Edwards AFB, CA 93524-7013	[2]Air Force Office of Scientific Research Bolling AFB, Washington, D.C. 20332	**8. PERFORMING ORGANIZATION REPORT NUMBER** **AFRL-PR-ED-TP-2002-161**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S NUMBER(S)** **AFRL-PR-ED-TP-2002-161**

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

To be presented at the AIAA Joint Propulsion Conference in Indianapolis, IN, from 8-10 July 2002.

14. ABSTRACT

20040114 018

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Leilani Richardson
Unclassified	Unclassified	Unclassified	A	13	**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

THE USAF ELECTRIC PROPULSION RESEARCH PROGRAM*

Ronald A. Spores
Air Force Research Laboratory Propulsion Directorate
Edwards AFB, CA 93524

Mitat Birkan
Air Force Office of Scientific Research, Bolling AFB,
Washington, DC 20332

Abstract

An overview of current electric propulsion research and development efforts within the United States Air Force is presented. The Air Force supports electric propulsion primarily through the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL) and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall direction for the programs comes from Air Force Space Command (AFSPC), with AFRL mission analysis used to define specific technological advances needed to meet AFSPC mission priorities. AFOSR funds basic research in electric propulsion throughout the country in both academia and industry. The AFRL Propulsion Directorate conducts electric propulsion efforts in basic research, engineering development, and space flight experiments. EOARD supports research at foreign laboratories that feeds directly into AFOSR and AFRL research programs. Current research efforts fall into 3 main categories defined loosely by the thruster power level. All three agencies are conducting research at the low-power regime ($P < 200W$), in support of emerging USAF microsatellite missions. Efforts in the mid-power range (500W to 5kW) is being shifted from research and development to thruster/spacecraft integration issues. The high power regime ($P > 30kW$) is realizing increased emphasis.

I. Introduction

In order to take advantage of the strong potential offered by electric propulsion, the United States Air Force (USAF) has developed a coordinated research program within the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL), and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall guidance for these research efforts comes principally from Air Force Space Command (AFSPC) in the form of a Strategic Master Plan (SMP). The SMP provides a 25-year USAF plan, detailed in terms of near-term (2000-2007), mid-term (2008-2013), and far-term (2014-2025) development priorities. AFRL and AFOSR perform mission analysis to determine the optimal propulsion systems for AFSPC missions, and then promote research programs to develop the technologies needed to achieve these missions. EOARD interacts with AFRL and AFOSR to develop research at European and former Soviet Union laboratories that feeds directly into the AFOSR and AFRL research programs. Near-term missions are generally served through commercial contracts at the System Program Office (SPO) level. The AFRL role in these efforts is one of technical advice, advocacy, and demonstration of new technologies to facilitate technology transfer to the commercial sector. The research role of AFRL and AFOSR is focused on the mid- and far-terms, with AFOSR directing the basic research that enables the AFRL to meet the far-term mission needs via a future advanced engineering program.

The AFRL technology development programs are coordinated with NASA and progress is evaluated through the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. IHPRPT is an national propulsion development program, which details specific performance advances for each technology area in a three-phase effort from 1995 to 2010. The IHPRPT baselines and goals were determined through a collaborative effort between AFRL, NASA and industry. The majority of AFRL electric propulsion funding falls under the guidance and constraints of the IHPRPT program.

AFOSR and AFRL also manage a number of contracts through the Small Business Innovative

* Presented as Paper JPC 02-3558 at the 38th AIAA Joint Propulsion Conference, Indianapolis, In, 7-10 July, 2002

Research (SBIR) and the Small-Business Technology Transfer Research (STTR) programs that feed into the core programs and are directed towards achieving the IHPRPT goals.

Historically, USAF electric propulsion research has been directed primarily at medium power technologies (500W–5kW) for stationkeeping, rephasing, and orbit topping applications. Electric propulsion in this class is becoming largely commercialized. Both arcjets and ion thrusters are now seeing widespread use on commercial satellites, indicating their availability for military applications. The exception is the Hall thruster. Whereas the Hall thruster has performance characteristics (specific impulse, thrust density) optimal for the on-orbit USAF satellite missions, to date it has only seen widespread operational use in Russia. The AFRL's interest in 5kW class Hall thrusters is declining. The technology is considered of sufficient maturity, and the commercial payoffs sufficiently large, that further performance advances would be accomplished most effectively in the private sector.

Opportunities continue for research that abets the Hall thruster commercialization by decreasing perceived risk associated with spacecraft interactions. AFRL and AFOSR are pursuing efforts to better understand the spacecraft-plume interactions through modeling and simulations, supported by laboratory and space measurements where possible. AFRL has contracted an effort with General Dynamics to decrease spacecraft interaction through the use of physical plume shields between the thruster and critical spacecraft surfaces.

With the decline in electric propulsion research in the mid-power range, the USAF emphasis has bifurcated toward the low-power (< 200W) and the high-power (> 30kW) regimes. Low-power electric propulsion research responds to the AFSPC priority for highly maneuverable microsatellites performing modular on-orbit servicing (MOOS) or flying in formation to enable missions such as a sparse aperture devices. Mission analysis shows that both high specific impulse and high thrust micropropulsion will be required to meet the low-power AFSPC missions, and the USAF is pursuing research in both areas. High-power electric propulsion research responds to the AFSPC priority for Orbit Transfer Vehicles (OTV) and the propulsion capability to rescue and reposition marooned assets that failed to achieve final mission orbit.

AFOSR supports industry and university research in low-power regime technologies such as colloidal thrusters, low power Hall thrusters, laser plasma thrusters and pulsed plasma thrusters (PPTs) for the high specific impulse maneuvers. EOARD supports 40W – 200W Hall thruster research in Russia. AFRL supports 200W Hall thruster, PPT development, laser-plasma thruster engineering, and electrodynamic tether development, often co-funding these efforts with AFOSR. EOARD and AFRL support separate research efforts in low-power, low-propellant, neutralizer technologies, essential for a low-power Hall thruster or a microsatellite-sized tether system. In-house research at AFRL, partially funded by AFOSR, has focused on miniaturized versions of the PPT and miniaturized chemical motors for high-thrust maneuvers.

A major part of the AFRL micropropulsion effort is the development of a low-power propulsion system for the TechSat21 spacecraft, scheduled for launch in late 2004. The contract for primary propulsion system on TechSat21 has been awarded to TRW for a 200W Hall thruster that will demonstrate IHPRPT Phase II goals for electrostatic spacecraft propulsion. TRW is subcontracting the thruster development to Busek and the propellant feed system to Moog. The Busek 200W Hall thruster was originally developed under AFRL and AFOSR SBIR contracts. A second AFRL effort on TechSat21 will be to demonstrate micropropulsion for attitude control using the AFRL MicroPPT. The MicroPPT developed for TechSat21 will demonstrate the IHPRPT Phase II goals for electromagnetic spacecraft propulsion.

The high-power regime is realizing increased research importance. AFRL has entered into a commercial partnership to research the effects of clustering Hall thrusters together in order to achieve high total system power. Ongoing AFOSR basic research on Hall thruster physics at the universities has beneficial impact both in the mid-power and high-power regimes.

In the following sections, various research programs supported by AFRL, AFOSR and EOARD are summarized with references to more complete descriptions. Summaries of the AFOSR funded efforts at the universities can be found in a companion paper from this same conference.[1]

Mission Analysis

In order to better focus its future technology development direction, AFRL performed a series of trade studies to examine propulsion priorities for spacecraft missions of interest to the Air Force. The project utilized a methodology and format similar to the NASA Advanced Space Transportation Program

(ASTP) Integrated, In-Space Transportation Planning (IISTP) process. Whereas the IISTP examined propulsion technologies for planetary exploration missions of interest to NASA, the AFRL study concentrated on earth centric missions of military relevance.

The missions examined (in order of priority) were: LEO – GEO Orbit Transfer Vehicle, GEO Comsat North-South Stationkeeping (NSSK), Combined Orbit Insertion/NSSK/Satellite Rephasing Mission, Satellite Inspection and On-Orbit Servicing, GEO Comsat Rephasing, Propulsive Attitude Control of a Microsatellite, Spacecraft Formation Flying, LEO Satellite De-Orbit, Highly Elliptical Orbit Insertion, Radical Plane Change (from LEO Equatorial Orbit).

A full range of spacecraft propulsion technologies; including chemical, electric, and solar thermal propulsion; were considered for each mission (at the appropriate power levels). The AFRL took the results of these studies and, in conjunction with the NASA Glenn RC, performed a joint agency technology prioritization. The technologies which were identified as deserving the strongest investment were: Hall Thrusters, Ion Engines, "Green" Monopropellants and Solar Thermal Propulsion.

Other technologies that were viewed as promising but having niche applications or are "High Risk / High Payoff" and should thus be pursued at a lower level of effort were: pulsed plasma thrusters, micro pulsed plasma thrusters, laser plasma thrusters, colloid thrusters, electrodynamic tethers and field emission electric propulsion (FEEP).

Overall, however, the key result was that there is no single "best" technology – AFRL and NASA need to develop a suite of solutions to meet a range of mission requirements including performance, trip time, power availability, integration issues, satellite size, system handling cost (propellant toxicity), and spacecraft contamination.

International Programs

Through the Air Force's European Office of Aerospace Research and Development (EOARD), AFRL is involved with several international organizations in basic research related to EP. These programs bring valuable innovation and expertise from Europe and Russia to the U.S.

At Universidad Politecnica de Madrid, research is ongoing to study the physics of the plasma sheath in Hall thruster discharges. Theories suggest that the secondary electron emission of the Hall thruster discharge may affect the discharge and possibly modify Hall thruster operational behavior. To validate these theories, researchers at CERN in Switzerland are making secondary electron yield measurements of a variety of Hall thruster insulator materials. These same materials are being tested inside low-power (100-200W) Hall thrusters at Kurchatov Institute in Moscow, Russia.

Also in Russia, researchers at TSNIIMASH are developing innovative diagnostics techniques for accurately characterizing the plume emitted from thruster with anode layer (TAL) in three dimensions. These techniques, both optical and electrostatic, will be used to map the plume from a single TAL, as well as a cluster of TALs operating simultaneously.

PPT research at Kurchatov Institute is advancing the understanding of PPT discharges in the 20-100 Joule range. Efforts include coupling a PPT discharge model to a propellant ablation model based on heat transfer from the discharge into the propellant face.

II. Low Power Electric Propulsion (< 200W)

Field Emission Cathodes

This Phase II SBIR, field emission (FE) cathode program with Busek Co. is nearing completion. Initially it focused on diamond emitters and was later expanded to include carbon nanotube (CNT) emitters. A CNT FE cathode is being tested prior to shipment to AFRL as a deliverable.

Busek grows its own CNTs using a proprietary process. The CNTs are deposited on an emitter substrate which is in close proximity (<0.010") to an electron extraction electrode called a gate. The gate is a highly perforated thin sheet of metal with high open area fraction (>50%). A positive voltage on the gate relative to the emitter extracts electrons from the CNT's. A typical cathode delivers up to 10 mA with gate voltages in the range of 200 to 400 volts and weighs about 20 grams.

With these demonstrated characteristics the CNT FE is ideal for high voltage low current EP such as FEEPs, colloids, micro-ion thrusters and perhaps even small electrodynamic (ED) tethers. It has been already successfully demonstrated as a neutralizer on a colloid thruster (under MDA/NASA program) and on FEEP thrusters by Centrospazio in Italy. To make the CNT FE practical for low power (≤ 200 W) Hall and ion thrusters requires a simultaneous increase in total current and reduction in gate voltage. Design improvements are continuously being pursued.

Micro Laser Plasma Thruster

A micro laser plasma thruster (μLPT) is currently in development thru a joint effort between Dr. Claude Phipps of Photonic Associates (PA), Albuquerque, NM and the University of New Mexico. This effort is funded jointly through an AFOSR STTR contract and AFRL for engineering development.

The μLPT is an alternative to the micro pulsed plasma thruster (μPPT) for meeting attitude control requirements in microsatellite-class spacecraft. Its sub-kg mass is about 10% of the reaction-wheel/torque-rod mass currently installed on TechSat21. The TechSat21 requirement of 75μN thrust on a single axis has been met while the requirement of 100N-s impulse per axis in a 3-axis thruster set is presently being pursued.

The laser plasma thruster takes advantage of the recent commercial availability of 4-watt diode lasers with sufficient brightness and 100% duty cycle to produce a repetitively-pulsed or continuous vapor or plasma jet on a surface in vacuum. The diode is a low-voltage device (3V) with electrical efficiency in excess of 50%. A lens focuses the laser diode output on a 100-μm diameter spot on the transparent side of a specially-prepared fuel tape. Passing through the tape without damaging it, the beam heats a specially prepared absorbing coating on the opposite side to high temperature, producing a miniature jet that generates thrust.

Repetitive-pulse operation has been found to be necessary to avoid steering of the plasma jet plume. Since target geometry constrains the new configuration to a maximum duty factor of 25%, to achieve 4W average power (sufficient for 75μN thrust with a 100% safety factor on standard materials), it was necessary to upgrade the diode laser source to 20W peak power capability. We did this by combining four JDSU 6380-A fiber-coupled lasers at the image plane of the target focusing optics. The diodes are capable of twice their CW power rating when operated in the 1-3-ms pulse duration range. Our standard ablatant contains a carbon-based laser absorber plus polyvinylchloride. One task of this effort is to incorporate energetic materials into the ablatants. Energetic ablatants are composed of carbon plus cellulose nitrate or a proprietary energetic material created by the Paul Scherrer Institut, Zürich. The micro laser plasma thruster using the energetic ablatants is projected to deliver 1mN @ 2 W average, Isp ~ 500 sec, .85kg wet mass and have a 1000 N-s total impulse.

Electrodynamic Tethers for Microsatellites

System analysis by AFRL for a LEO application has shown that an electrodynamic tether can deliver a total impulse divided by wet mass that is more than a factor of 10 greater than a LES 8/9 Pulsed Plasma Thruster. The predominant technical issues that need to be resolved are low mass electron sources and tether lifetime. The inherent complexity and risk associated with deploying and operating a tether can only be diminished through a flight demonstration.

Tethers Unlimited Inc. (TUI), under a Phase II SBIR, has designed and built prototype hardware for a very small tether device intended to fly as a secondary payload on a microsatellite mission; See figure 1. It is designed to present no risk to the spacecraft's primary payloads, remaining completely dormant until the spacecraft has completed its mission. At the end of the spacecraft's mission, the tether device will deploy a 2 km long interconnected-multiline conducting tether upwards from the microsatellite, and will use passive electrodynamic drag to lower the orbit of the microsatellite. To minimize the mass of the device, TUI developed a new tether deployment mechanism in which the tether deployer ejects itself away from the spacecraft and becomes the tether endmass ballast. Laboratory testing of this deployment mechanism indicates that it can successfully deploy a multiline tether at tensions low enough for successful deployment. TUI evaluated several cathodes for this experiment, including plasma contactor technologies and finally selected a thermionic device based upon a COTS dispenser cathode for its minimal mass and technology maturity. With this tether hardware, a "barebones" experiment to deorbit a 100 kg microsatellite can be implemented with a total tether system mass of < 2.5 kg, which is less than the propellant required to fully deorbit such a microspacecraft using hydrazine thrusters. A more capable experiment, with active control of tether dynamics and diagnostics on tether performance and dynamics, can be implemented with a total mass of 3.5 kg. Current efforts are focused on designing appropriate power conversion and control elements to enable the tether system to operate in a propulsive mode for applications such as long-duration stationkeeping and raising the orbit of Shuttle SHELS-launched microsatellites to high-LEO altitudes. The ability of the tether system to provide thrust without consuming propellant will enable microsatellite systems to perform large orbital maneuvers with very high payload fractions.

MicroPPT Program

A class of miniaturized pulsed plasma thrusters (PPTs), known as MicroPPTs,[2] is currently in development at the Air Force Research Laboratory. The MicroPPTs use a surface discharge across solid Teflon™ propellant to provide precise impulse bits in the 10 μN–s range. In the near term, these thrusters can provide propulsive attitude control on 100kg class spacecraft using 1/5th the dry mass of conventional torque rods and reaction wheels. Eventually these thrusters are designed for primary and attitude control propulsion on future 25–kg class spacecraft.

A 3–electrode configuration, shown in Figure 2, has been implemented which removes nearly all of the legacy technology from the LES 8/9 PPT, including the spark plug and ignitor circuitry.[3]

Efforts to characterize MicroPPT performance and the thruster plume are underway. To this end, a modified torsional thrust stand has been developed for the purpose of accurately measuring the low–level thrust generated by the MicroPPT. A Herriott cell interferometer is used to establish the electron and neutral densities in the thruster plume. Comparison of the measured electron density with modeling predictions shows close agreement. In addition, a Pockels cell has been developed to provide a zero–impedance MicroPPT breakdown voltage measurement, and an intensified CCD array has been used to characterize the divergence of both the thruster plume and the late–time particulate emission.

Thermocouple tests indicate that providing a thermal path from the thruster to a heat sink can significantly reduce temperatures in the MicroPPT tube. Thermal vacuum tests have demonstrated MicroPPT functionality from –60°C to +60°C. Long–duration MicroPPT tests result in exhausting all available propellant. This quickly results in thruster shutdown as the electrode gap becomes too great.

Spacecraft interaction tests indicate that the plasma plume shape can be well–characterized and accounted for in spacecraft integration. The divergence of the late time vaporization, which evolves after the plasma, is strongly linked to the recession of the Teflon™ in the MicroPPT. An initial recessed fuel profile would potentially reduce solid Teflon™ deposition on spacecraft surfaces.

Micronewton level performance measurements on the MicroPPT were accomplished at AFRL by modifying the NASA-Glenn PPT thrust stand developed by Tom Haag[4], to operate in a forced resonance oscillation mode. As reported at JPC 2000[5], this technique reduced the measurement uncertainty from 10 micronewtons down to 5 micronewtons. Using a crude manifestation of this technique AFRL successfully measured MicroPPT thrust levels of 5 μN/Watt during a time period in which the Teflon™ propellant receded 3 diameters back into the cathode shell. Based on the improved signal-to-noise using the new technique, it was expected that the thrust measurement uncertainty could be simply reduced to 0.5 micronewtons. The limit at that time was uncertainties associated with the applications of the thrust, calibration weights, and a small amount of drift in the thrust stand.

Cooperation with USAFA

The US Air Force Academy has earmarked the AFRL MicroPPT as the primary attitude control system for FalconSat 3, part of USAFA's cadet–built research satellite program. In a joint effort to capitalize on the resources at USAFA, vibration and shock testing of a flight–like MicroPPT, depicted in Figure 3, has commenced at the Academy.

Utilizing the USAFA vibration table, the MicroPPT was subjected to a Delta IV ESPA level vibration spectrum as well as a 100 g separation shock. Ensuing diagnostic tests indicated that the MicroPPT retained full functionality and all critical components survived.

Further coordinated efforts in the USAFA facility will involve vibration tests on multi–axis MicroPPT designs. Furthermore, newer thruster package designs and potting materials will be investigated. Additionally, an AFRL/JPL flight sensor package will be subjected to similar vibration and shock spectra to ensure survivability of the diagnostics array during liftoff and faring separation.

Micro Newton Thrust Stand

A micro-Newton thrust stand is being developed by Busek under a Phase II SBIR which will be capable of resolving 0.1 μN forces. The target thrust to thruster system mass ratio is 10^{-8}. The key design feature is a magnetic suspension of the movable portion of the thrust stand, referred to as the Maglev.

The magnetic suspension reduces facility vibration effects and allows frictionless rotational motion of the suspended platform. The thruster under test is placed on this platform and its thrust creates a torque about the vertical axis. The maglev operates in 2 modes. In the first mode called force nulling, an electrostatic force opposes the thrust to maintain the thrust stand rotational platform displacement near zero and measured optically. In the second mode the platform is allowed to freely rotate thus allowing direct measurement of the total impulse by observing rotational velocity changes of the suspended platform. When using this mode the entire thruster system is untethered with all propellants and power on board of the thrust stand rotating platform. Commands and data are transmitted wirelessly through a multichannel bi-directional RF link thus allowing truly unhindered frictionless rotation. It is anticipated that the total impulse mode will be most useful for pulsed thrusters such the PPT and the force nulling mode may be preferred for steady state thrusters such as the colloid and FEEP. The first prototype of this maglev thrust stand has been demonstrated. Second prototype demonstration with a colloid and μPPT thrusters is planned for fall 2002.

TechSat21 Propulsion Flight Demonstration

The Technology Satellite for the 21st Century (TechSat 21) is an Air Force Research Laboratory (AFRL) technology demonstration mission from the Space Vehicles Directorate in Kirtland AFB, NM. The TechSat 21 mission will demonstrate space-based, sparse-aperture sensing and formation flying, in conjunction with key microsatellite technologies. These technologies include thin-film flexible solar arrays, advanced avionics, inflatable booms, lithium-polymer batteries, and advanced micropropulsion. Three identical TechSat 21 spacecraft will be launched from a single Evolved Expanded Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring in late 2004. The three 150-kg spacecraft will be placed in an initial formation with safe separation distances for on-orbit initialization and checkout. Following the on-orbit checkout, the propulsion subsystem will be used to initialize a series of four formations over the course of the one-year mission [6,7,8] into a flight-ready design. The TechSat 21 primary propulsion is responsible for the initialization of the cluster, formation keeping, and cluster reconfiguring for the one-year mission.

To satisfy the TechSat 21 propulsion objectives and to provide a demonstration opportunity of the IHPRPT Phase II electromagnetic goals, the AFRL Propulsion Directorate awarded a contract in September, 2000 to TRW for the development of a 200-W Hall thruster system. Subcontractors on the team include Busek Co. for the development of the thruster and the cathode, and Moog, Inc. for the development of the xenon feed system (XFS). TRW is responsible for the development of the power processing unit (PPU), as well as the system engineering, integration, and qualification testing. Figure 4 shows the current layout of several of the external components of the propulsion subsystem on the TechSat 21 spacecraft. Not shown are the internal components, which include the XFS, the PPU, and the interface electronics unit for the on-board propulsion sensors.

In addition to the Hall thruster system, the TechSat 21 flight will also serve to demonstrate the AFRL MicroPPT[3] and a suite of miniaturized flight sensors[9]. The Micro-PPT can be used as either attitude control for a 150-kg class spacecraft (as was the original intent on TechSat 21), or as primary propulsion on a <25kg class spacecraft. The TechSat 21 flight will be used to validate the MicroPPT design maturity, verify its performance, and develop operational profiles for on-orbit applications. The sensor suite will measure all of the interactions of the Hall thruster and MicroPPT on the spacecraft, and includes a significant amount of ground testing and modeling and simulation to ensure the flight results can be applied to future DoD and commercial spacecraft.

Hall Thruster System Status

The Hall thruster system development has made significant progress towards attaining engineering model hardware suitable for integrated spacecraft testing. As described in previous articles[10], the philosophy of the program has been focused on building hardware, and putting that hardware through a rigorous test sequence as early in the program as possible. While the thruster and cathode already had a significant amount of testing completed due to their SBIR program heritage[10], the PPU and XFS required a lot of early testing to validate their design. In light of this approach, several key tests were successfully completed over the last year, resulting in a Hall thruster system that has a high maturity level and is close to being ready for delivery for spacecraft-level integrated testing.

After a successful campaign to update the thruster and cathode to a flight design, the engineering model (EM) assembly was built and tested to verify performance and environmental requirements. The tests included: thrust, I_{SP} measurements, random vibration and shock testing, and a series of cathode cycle tests to verify the heater design. Typical performance of the EM thruster and cathode as measured at Busek were 12 mN thrust, 1,370 seconds total I_{SP}, and 37.8% efficiency. Although there were some setbacks along the way, the random vibration and shock, as well as the cathode heater cycle tests, were all completed successfully. Likewise, the XFS and PPU underwent extensive component-level testing and typically performed better than mission requirements. While the bulk PPU efficiency was near 87%, the efficiency of the discharge power supply (which powers the thruster discharge) routinely exceeded 92%, and the design has proven to be robust enough to fire continuously in vacuum for as long as 60 minutes without issue. The XFS, too, has routinely shown steady mass flow performance from <75 psia up to >2,100 psia at flow rates below 1 mg/sec. Furthermore, all of the EM components have been delivered well within the mass and power estimates established early in the program.

Following the component tests, individual assemblies were integrated together and incrementally tested to verify there were no interaction issues. These tests started with the thruster and cathode integrated with the XFS, and then expanded to include the PPU – both inside and outside of the vacuum tank. As shown in Figure 5, the integrated system was successfully fired in vacuum and all test parameters indicated the performance was identical to that measured at Busek.

The remaining work on the Hall thruster system will be focused on resolving a flow control interaction issue identified in the integrated system test at TRW, as well as performing the remaining qualification tests on the EM hardware. Following the completion of these last tasks, the existing EM hardware will be integrated onto the spacecraft panel late this calendar year with all of the remaining propulsion subsystem components, and delivered for spacecraft integration tests in March, 2003.

MicroPPT Flight Hardware Development Status

While the general development of the MicroPPT is discussed earlier in this paper, the specific development of the hardware for TechSat 21 is also progressing well. Since the thruster is much less complicated than other propulsion systems, the spacecraft requirements and interface were fixed, which allowed the development of the thruster itself to continue unabated[3]. This interface has remained unchanged for many months, while the thruster itself has undergone significant improvements in performance and stability. In addition to vib testing at the US Air Force Academy, the thruster was also tested over a broad range of temperatures in a vacuum environment at AFRL using a newly constructed vacuum-compatible thermal shroud. Thruster operation was verified from –100 deg C to +20 deg C at pressures less than 5×10^{-5} Torr with no anomalous operation observed.

Propulsion Sensors Development Status

The TechSat 21 propulsion sensors are derived from the successes of the ESEX program[11], but are dramatically reduced in size and mass with a significant increase in capability. As described above, the goal of the propulsion instruments is to measure the interaction of the thrusters with the spacecraft and be used to produce a set of integration guidelines for future thruster uses. As such, there is a strong modeling and simulation component of this effort that is being led out of AFRL, with collaborations from both the industry and academic sectors. The on-board sensors are comprised of six solar array segments, ten radiometric and ten photometric sensors, two electron probes, and a miniature ion energy spectrometer shown in Figure 6. The propulsion instrument electronics (PIE) rounds out the system and provides the command, telemetry, and power interfaces to all of the instruments from the spacecraft. The PIE is fully programmable on-orbit and is capable of performing a wide variety of operations, such as varying the sampling rate up to 1 kHz, with highly accurate measurements, including current measurements of less than 1 picoAmp. To date, all sensors have undergone prototype testing, and some are approaching an EM. The first EM PIE has already been delivered and will be tested over the coming months with simulators, the prototype sensors, and ultimately in conjunction with the thruster.

Rapidly Starting Hall Thruster Cathode

The TechSat 21 200 W Hall thruster can operate in a pulsed mode, as well as its traditional steady-state mode, delivering precisely controllable, repetitive or single impulse bits of arbitrary magnitude, the latter dictated by the duration of the discharge pulse. To fully capitalize on the pulsed operation of a Hall thruster requires a cathode capable of rapid starting to minimize the time from the command for thrust to the time the discharge pulse can be initiated. The most significant delay occurs during the time required to heat the cathode emitter and the time to establish expellant within the cathode.

In this Phase I SBIR effort, Busek will evaluate several methods to rapidly starting an electron source for the thruster. Approaches to be analytically and experimentally characterized include a derivative of their standard hollow cathode designed for rapid heating of the emitter insert and novel approaches for heaterless style cathodes. Preliminary experiments will be conducted to determine characteristic turn-on times. The most promising approaches will be further investigated for thermal and discharge cycle capability. In Phase II, prototype cathodes will be designed and fabricated for integrated testing with a Hall thruster in the pulsed and steady-state operating modes.

Single Converter Hall Thruster Power Processor
State-of the-art electric propulsion technology is complex and costly for many mission applications. Of the subsystems that comprise the propulsion system, the most fruitful to achieve a significant reduction in cost, complexity, and mass is the power processing unit.

In Phase I, Busek Co. will demonstrate the feasibility of a new power processing architecture that replaces the four (4) main DC to DC converters of the conventional PPU with a single converter architecture. The single converter design utilizes a high power converter to provide the discharge power to the thruster and both heat and start the cathode. The proposed converter topology will be a derivative of Busek's nominal 500 W (350 V; 1.5 A) discharge converter developed and demonstrated for TechSat 21. In addition, Busek will develop a modified cathode design capable of heating at low input current. Experiments will be performed to develop a starting sequence and operating algorithm for the thruster. The long-term objective is to develop a simplified flight qualification low power Hall thruster system with high performance and low system mass.

Space Shuttle-compatible Propulsion Module
The AFRL is currently investigating shuttle-compatible Propulsion Modules (PM) through its Small Business Innovation Research (SBIR) program. This particular SBIR topic seeks to address requirements set forth by the Air Force Space Test Program (STP) to acquire the ability to raise the orbit of small, experimental satellites deployed from the payload bay of the space shuttle (SS). Integral to this effort is the ability to meet NASA Shuttle Hitchhiker Experiment Launch System (SHELS) safety requirements. Currently, there exists no propulsion system capable of performing the STP-specified orbit raising while meeting SHELS requirements.

Busek Co. Inc. has been contracted to evaluate a number of systems capable of raising a 125 kg payload to a 700+ km final orbit. Preliminary analyses have identified a 200 W Hall thruster and a 100W resistojet as the most promising technologies. In this Phase I effort, Busek will refine their PM analyses and provide designs for the top two PM systems. Busek will also perform extensive safety risk analyses to verify compliance with SHELS.

III. Mid-Power Electric Propulsion Research

High Performance Hall System
Although very satisfied with the technical effort of its prime contractor, Atlantic Research Corporation, AFRL has discontinued funding of the 4.5kW High Performance Hall System (SPT-140) program due to a combination of reasons. Availability of flight-qualified Russian SPT-140s for all U.S. Military uses could not be assured to AFRL's satisfaction. In addition, rapidly developing domestic engines in the same class made it difficult to justify continued funding of a non-domestic engine.

4.5kW Testing for Advanced EHF Satellite
The AFRL is working closely with General Dynamics Space Propulsion Systems (GD-SPS) to further improve performance of the GD BPT-4000 Hall thruster manifested on the Advanced Extremely High Frequency (AEHF) satellite. The current Engineering Model thruster performance successfully exceeds average mission requirements, however, an initial performance drop over the first several hundred hours of operation has been observed. Based on results from earlier developmental thruster models that did not display this performance drop, GD and AFRL have initiated a joint investigation to explore options to reduce or eliminate the observed initial performance decline. The potential exists for as much as a 6% increase in mission average performance for the AEHF nominal mission.

GD has identified a number of design changes made to the initial laboratory model BPT-4000 thruster. The effect of these design changes will be evaluated through a series of 100 - 150 hour tests in the AFRL high vacuum Hall thruster test facility, Chamber 3. This will include baseline and post-test performance measurements as well as several probe-based plume measurements to isolate the cause of the initial performance decline. Faraday probes will monitor total ion current and beam divergence. A retarding potential analyzer (RPA) will be employed to monitor the ion energy distribution. Langmuir probes will provide plasma potential measurements to evaluate cathode-discharge coupling efficiency. A magnetic field sensor will monitor the thruster magnetic circuit.

Based on the results of the AFRL tests, the possibility exists for immediate incorporation of design modifications, providing a direct impact on initial AEHF satellite system capabilities.

IV. High-Power Electric Propulsion Research

AFRL continues work on a program to develop Hall thruster systems that operate at power levels well in excess of state-of-the-art. The current program goal is for operation in the 100kW to 150kW range. This effort addresses the AFSPC priority for orbit transfer vehicles (OTV) and rescue vehicles capable of repositioning and rescuing of marooned space assets that have failed to achieve final mission orbit. To address the issue of high levels of on-orbit electrical power, the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is developing PowerSail[11]: a two-phased program to demonstrate high power (100 kW to 1 MW) capability in space using a deployable, flexible solar array constructed of thin-film photovoltaics. Use of thin film photovoltaics in place of conventional solar arrays is projected to decrease specific mass and cost while increasing packageability.

The current objective of the high power program is to understand the physics and practical implications of interactions within clusters of Hall thrusters. The clustering project is experimentally characterizing the interactions of the plumes with thrusters that are relatively inexpensive to operate and small enough not to require extensive vacuum facilities. In general, the primary advantage of a clustered approach to 100 kW-class power levels concedes performance in favor of cost. Thruster development is currently being performed at Busek Co. under several SBIR programs. Recently, a cluster of 200 W Hall thrusters has been delivered to AFRL for preliminary cluster research. A second cluster at intermediate power (600 W) is being developed to examine issues such as cathode current sharing, electrical crosstalk, and plume interactions. At AFRL, the array of 200 W Busek BHT-200-X3 Hall thrusters has been tested for several hundred hours; see figure 7. A paper will be presented detailing plume interactions[12]. Another paper will detail a thruster start-up transient that can affect cluster operations[13]. Other measurements of the cluster of BHT-200-X3 Hall thrusters, including ion current density, electrical crosstalk, and cathode current sharing have also been taken[14].

The greatest interaction of electrically independent thrusters within the cluster occurs during initial start-up after thruster exposure to atmospheric, or regenerated, water vapor. During the high anode current transient period, the individual thrusters randomly enter and exit a high anode current mode. Further, the thrusters sometimes appear to be linked as they enter and exit the high anode current mode. This is contrasted with the single thruster transient where the thruster anode current gradually transitions to a steady state anode current. In all cases, the anode current transient is characterized by a high frequency (~18 kHz) on/off behavior in the main discharge. This oscillation appears to increase the average plasma conductivity through the radial magnetic field, thus increasing the time averaged anode current. It is important to note that once the thrusters are conditioned and if the cluster is electrically unconnected, no significant interaction is observed. At this time, the operation of clusters of independent thrusters appears to be the simplest implementation. Future efforts will examine the interactions between the main discharges implied by the start-up behavior which are assumed to continue to a lesser degree into steady state operation.

Ion current densities of single plumes were measured and compared to the plume of two simultaneously operating thrusters using Faraday probes. Initial results imply that the plume of two thrusters is slightly less divergent than that expected by the linear superposition of the individual plumes. This result may be due to the modification of near plume magnetic fields. These results are preliminary and issues related to the use of a Faraday probe require further exploration.

Cathode current sharing has also been shown to be an issue. When two cathodes were tied to a common ground, one cathode would dominate the emission current and in the case examined, the dominant provided 90% of the combined current. When a main discharge was coupled to an adjacent thruster's cathode, the coupling was poor with approximately 15% higher than normal anode current. It is believed that a higher plasma density in the intervening volume between a cathode and distant discharge chamber will improve due to increased plasma conductivity. This implies that larger clusters of Hall thrusters will require either isolated cathodes for each component thruster, or common neutralizers with high flow rates, such as arcjets.

AFRL is also collaborating with the University of Michigan, Ann Arbor, to construct a high power cluster of 5 kW class P-5 thrusters. Several of the jointly developed thrusters will be delivered to the university later this year. Currently, modeling efforts are underway to anticipate the introduction of the cluster of P-5 Hall thrusters into the University of Michigan vacuum facility[15,16]. AFRL is also collaborating with Stanford University examining the use of arcjets as neutralizers for clusters of Hall thrusters. This effort has experimentally demonstrated the neutralization of a Hall thruster using low power helium and hydrogen arcjets. Additional efforts at Stanford are being directed toward the development of non-intrusive plasma diagnostics.

Plume Investigation to understand Clustering Interactions

Another effort, in the process of being funded by EOARD, is with TSNIIMASH Export, Moscow, Russia, characterizes the plume of their existing D-55 thruster. This program will investigate atomic and molecular processes in the plume region via emission spectroscopy. This effort also starts to investigate the plume interaction issues of a clustered set of Hall thrusters for high power applications.

V. Modeling and Simulation

AFRL is leading a national team in the development of a of a new software package named COLISEUM, which is capable of self-consistently modeling plasma propagation and interactions with arbitrary 3-D surfaces using adaptive, unstructured gridding techniques.[17] The applications of COLISEUM are wide-ranging, but include simulating engine test configurations inside vacuum chambers, and predicting sputtering and re-deposition on spacecraft surfaces. Currently, COLISEUM is being used in support of two Air Force missions: TechSat 21 and MILSATCOM Advanced EHF.

COLISEUM allows users to easily define complicated 3-D geometries using off-the-shelf CAD software, then select from a set of plasma expansion models of varying fidelities and run-times to perform the solution. With this system, low fidelity models can be used to verify the geometry and boundary conditions, and to obtain first-order predictions. Then, higher fidelity models can be used to obtain the most accurate predictions available, after higher computation times.

Figure 8 shows how COLISEUM can be used to superimpose HET plumes onto complicated 3-D geometries. In this case, a generalized thruster integration test is being simulated inside a 2-meter-diameter vacuum chamber. Figure 9 shows the resulting calculation of deposition of chamber wall material on the test fixture.

EP device modeling is being pursued through AFRL collaborations with academia and industry. At the University of Michigan, micro-PPT models are being developed which, for the first time, are able to accurately predict and propagate the late-time ablation of PPT propellant. The AFRL/MIT Hall thruster code, HPHall, is being improved through a contract with Advatech Pacific, Inc. HPHall is currently being used by AFRL and by the University of Washington to predict possible effects of Hall thruster insulator material on performance.[18]

VI. AEDC Test Facilities

The Arnold Engineering Development Center (AEDC) at Arnold AFB has recently augmented its existing space simulation thermal vacuum testing capability for electric propulsion subsystems. The 12V Space Simulation Chamber is 12ft. in diameter by 35ft. high and is lined with 77K LN2 cryopanel surfaces (Figure 10). The chamber is capable of thruster tests ranging from under 1 kW to 20 kW in power, and with mass flow rate ranging from 1 to 50 mg/sec Xe. Plume integration and contamination are two of the key issues associated with EP system-level integration that this chamber is designed to address. The AEDC chamber requirement was that the operating back pressure of the facility be no higher than 10^{-6} torr at any time. The chamber has a GHe-cooled inner liner (shroud) which can be maintained at 10K. The chamber is cryogenically pumped using a large aluminum cryopump, cooled by a 3kW gaseous helium refrigerator. The pumping speed is augmented by using a series of baffles to manage the energy transport from the thruster ions to the cryopump. The power input by the thruster is further managed by the use of liquid nitrogen cryopanels that line the entire inner surface of the chamber.

The pumping performance of the 12V Space Chamber was demonstrated in a series of three tests conducted from December 2000 to January 2002. The test article for this check out was the laboratory version of the General Dynamics BPT-4000; this is a 4.5kW Hall Current Thruster (HCT) and is the pre-engineering design model for the thruster to be integrated as a mission-enabler on the Advanced EHF satellite. During the tests, chamber pressure was measured at 1.5×10^{-6} torr and pumping speed is estimated to be about 3×10^{6} liters/second.

VII. Summary

The Air Force supports electric propulsion primarily through AFOSR, AFRL and EOARD. Overall direction for the programs comes from AFSPC, with AFRL mission analysis used to define specific technological advances needed to meet the AFSPC mission priorities. Current programs are well grouped into 3 categories defined by the thruster power level. All three agencies are currently focusing their primary research in support of the emerging USAF microsatellite missions, due to the current lack of high performance flight-qualified propulsion at very low power levels ($P < 200$ W). Emphasis on research in the mid-power range (500W to 5kW) is greatly diminishing with the conclusion of the 4.5 kW HPHS Hall thruster development program. AFRL has recently begun to increase emphasis on very high power levels ($P > 30$kW).

VIII. Acknowledgements

The authors appreciated contributions to this paper from Vlad Hruby, Busek Co.; Stu Bushman, W.E.R.; Dave Pruitt, AEDC; and the researchers at AFRL, Edwards AFB.

IX. References

[1] P. Wilbur, "Review of the EP Activities of the US Academia," 38th AIAA Joint Propulsion Conf., paper AIAA-20021-3560, Indianapolis, In, July 7-10, 2002.

[2] G. G., Spanjers, "Micro Pulsed Plasma Thruster having Coaxial Cable Segment Propellant Modules," Patent Number US 6,269,629 awarded Aug 7, 2001.

[3] G. G. Spanjers, et al., "AFRL MicroPPT Development for Small Spacecraft Propulsion," 38th Joint Propulsion Conference, AIAA Paper 2002-3974, July 2002.

[4] T. W. Haag, "PPT Thrust Stand," 31st Joint Propulsion Conference, AIAA 95-2917, July 1995.

[5] F.S. Gulczinski, et al., "Micropropulsion Research at AFRL," 36th AIAA Joint Propulsion Conf., AIAA paper 2000-3455, Huntsville, AL, July 17-20, 2000.

[6] M. Martin, P. Klupar, S. Kilberg and J. Winter, "TechSat 21 and Revolutionizing Space Missions Using Microsatellites," Proceeding of the 15th Annual AIAA/USU Conference on Small Satellites, Aug 2001, Logan, UT.

[7] A. Das, and R. Cobb, "TechSat 21 - Space Missions Using Collaborating Constellations of Satellites", Proceeding of the 12th Annual AIAA/USU Conference on Small Satellites, Sep 1998, Logan, UT.

[8] A. Das, R. Cobb, M. Stallard, "TechSat 21: A Revolutionary Concept in Distributed Space-Based Sensing," AIAA Defense and Civil Space Programs Conference and Exhibit, Paper no. AIAA-98-5255, Oct 1998, Huntsville, AL

[9] L. K. Johnson, D. Conroy, G. G. Spanjers, and D. R. Bromaghim, "Propulsion Instruments for Small Hall Thruster Integration," 27th International Electric Propulsion Conference Paper No. IEPC-01-167, Oct 2001, Los Angeles, CA.

[10] V. Hruby, J. Monheiser, B. Pote, C. Freeman, and W. Connolly, "Low Power Hall Thruster Propulsion System," 26th Intl. Electric Propulsion Conference, IEPC-99-092, Sep 1999, Kitakyushu, Japan.

[11] T. Meink., et al., "PowerSail – A High Power Solution," AIAA Paper 2000-5081, AIAA Space 2000, Long Beach, California, September 2000.

[12] B. Beal, A. Gallimore, and W. Hargus, "Preliminary Plume Characterization of a Low-Power Hall Thruster Cluster," AIAA-2001-4251, Joint Propulsion Conference and Exhibit, 7-10 July, 2002, Indianapolis, IN.

[13] W. Hargus and B. Pote, "Examination of a Hall Thruster Transient," AIAA-2002-3956, 38th AIAA Joint Propulsion Conference and Exhibit, 7-10 July, 2002, Indianapolis, IN.

[14] W. Hargus and G. Reed, "The Air Force Clustered Hall Thruster Program," AIAA-2002-3678, 38th AIAA Joint Propulsion Conference and Exhibit, 7-10 July, 2002, Indianapolis, IN

[15] M. Walker, A. Gallimore, C. Cai, and I. D. Boyd, "Pressure Map of a Facility as a Function of Flow Rates to Study Facility Effects," AIAA-2002-3815, 38th AIAA Joint Propulsion Conference and Exhibit, 7-10 July 2002, Indianapolis, IN.

[16] C. Cai, and I.D. Boyd, "Computation of Neutral Gas Flow from a Hall Thruster into a Vacuum Chamber," 23rd International Symposium on Rarefied Gas Dynamics, July 2002.

[17] J. M. Fife, et al., "The Development of a Flexible, Usable, Plasma Interaction Modeling System," AIAA-2002-4267, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, Indiana, 2002.

[18] J.M. Fife. and S. Locke, "Influence of Channel Insulator Material on Hall Thruster Discharges: A Numerical Study," AIAA-2001-1137, 39th AIAA Aero. Sciences Meeting, Reno, NV, 8-11 Jan. 2001.

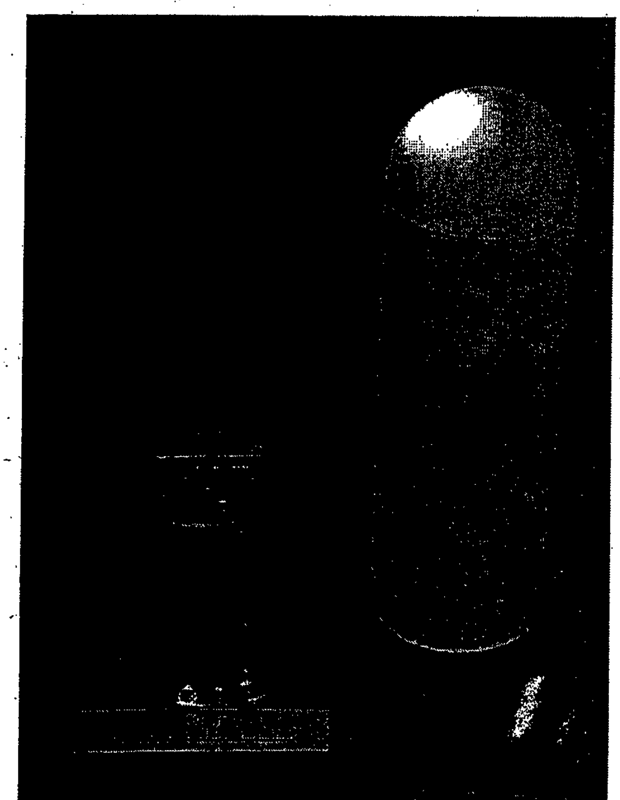

Figure 1. The prototype Microsatellite Propellantless Electrodynamic Tether (μPET) avionics and deployer

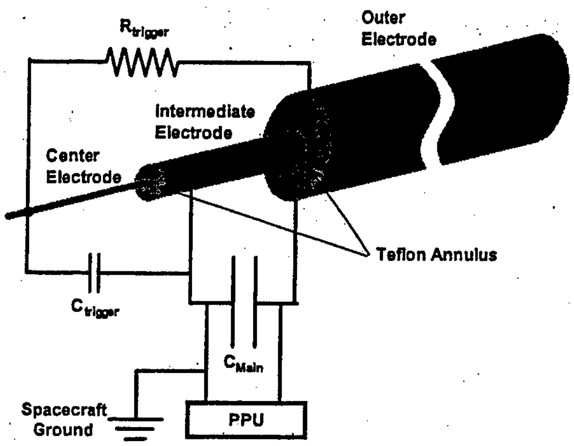

Figure 2: 3–Electrode MicroPPT configuration

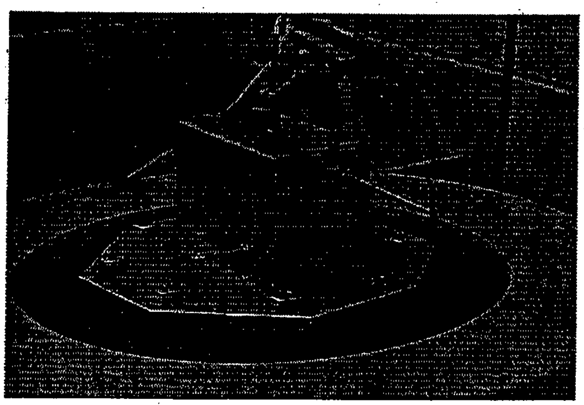

Figure 3 – A prototype MicroPPT during vibration testing at USAFA

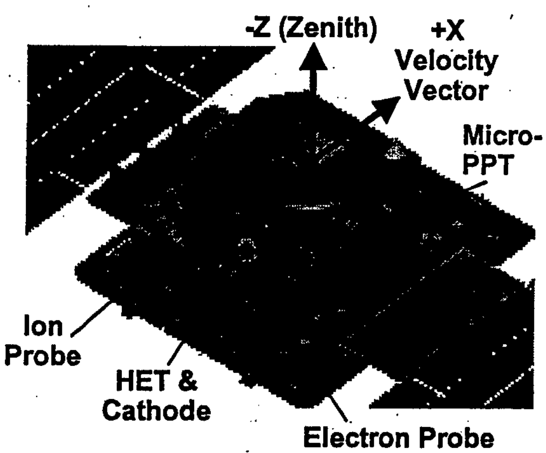

Figure 4. Layout of the Propulsion System Components on the TechSat 21 Spacecraft

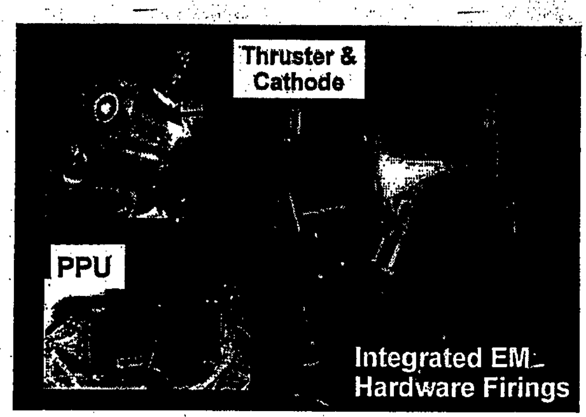

Figure 5 – TechSat 21 Hall Thruster and Cathode Firing During Integrated Testing

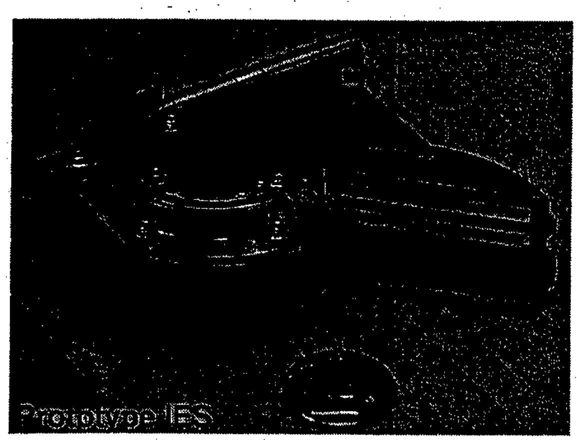

Figure 6. TechSat21 Prototype Ion Energy Spectrometer

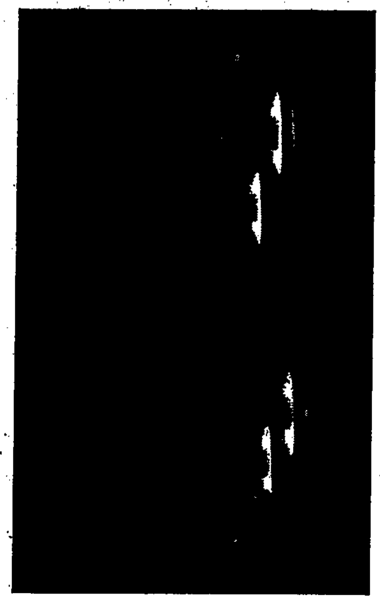

Figure 7. Four 200W Hall Thrusters firing at AFRL

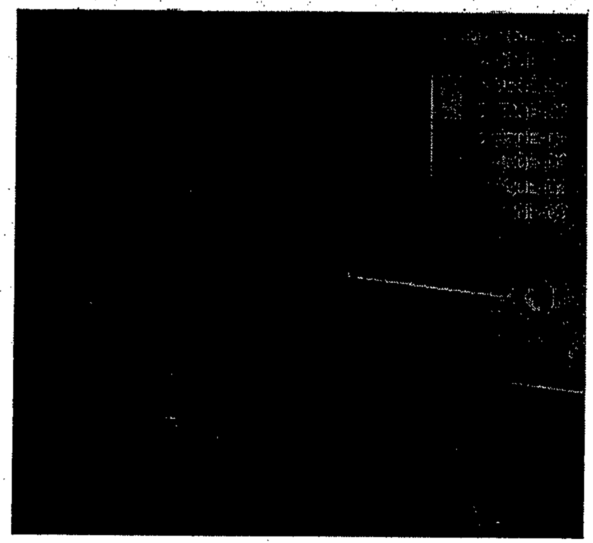

Fig. 9. Redeposition rate of aluminum from the chamber wall to instruments and surfaces on an HET test fixture

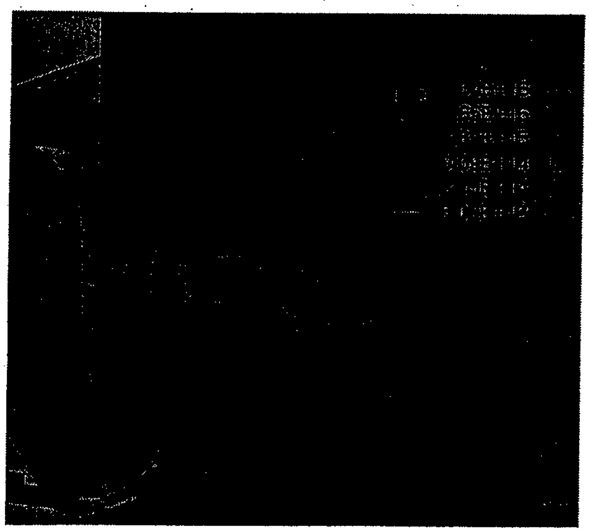

Figure 8. Slice showing plasma density from a 200-Watt HET firing inside a vacuum test facility

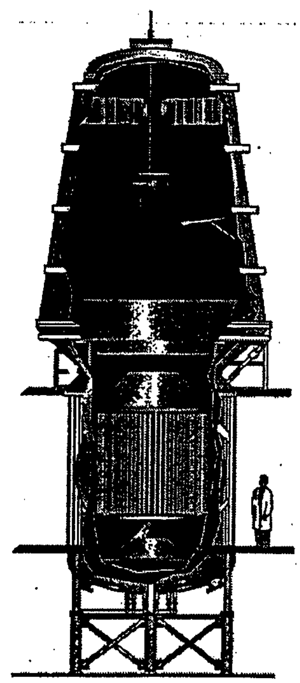

Figure 10. AEDC Space Chamber with cryopumps